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FIRST RESULTS FROM THE INTERNATIONAL SEISMIC MONTH

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Massachusetts Institute of Technology

Prepared for:

Electronic Systems Division
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2 July 1973

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14. KEY WORDS

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FIRST RESULTS FROM THE INTERNATIONAL SEISMIC MONTH

INTRODUCTION

In January 1972 seismologists from several countries met in Cambridge, Massachusetts, to discuss progress in seismic techniques for detecting and identifying underground nuclear explosions. At this meeting there was a clear interest in having a better assessment of present-day seismic signal detection capabilities. Issues of detectability are at the center of discussions on seismic monitoring because they define thresholds below which either there will be no data at all on which to make judgements or the data will be so sparse that the answers to crucial questions are unreliable. As a result of the discussions several groups of seismologists agreed to collaborate in an informal way in putting together a new assessment of detection capability. This short report describes the techniques used in the study and the first results to emerge from it. At this stage we do not wish to draw conclusions from the data presented.

NETWORK EVALUATION

Two approaches are possible to answering questions of detectability by a network. Both have been extensively reported on during the last few years, particularly in conjunction with presentations at Geneva and in the SIPRI meetings.

The first involves computer calculations of detectability for real or hypothetical distributions of seismometers at each of which ground noise characteristics are specified. Seismic events of given magnitudes are imagined to be placed all over the earth and the computer decides for each event whether it can be declared to be detected, on the basis of established amplitude/distance relationships and signal-to-noise values calculated at each station in the network. The outcome of such experiments is usually a contoured map of the world in which contours join points at which events of equal magnitude are just satisfactorily detected (i.e., the contours denote detection thresholds). This approach is most valuable in early stages of evaluating the capability of a network or the effect of the addition of new instruments to a network before the investment is made.

However it does suffer from certain disadvantages. The earth is enormously complex and whilst it is generally possible to predict the size of seismic signals at a given station to better than a factor of five, it is unlikely that in the near future the earth will be sufficiently well studied to make prediction to better than a factor of two possible. Further, every earthquake signal is followed by a 'coda' of scattered energy which may last for anything from a few minutes to several hours. During this time the effective 'noise' level is much higher at seismic stations, and so the network capability is diminished. As a very rough guide 10% of all surface waves go undetected at any one station because of interference from prior events. Thus networks have a time de-

pendent sensitivity, and since the coda level is not as yet a very predictable quantity, it is not easy to estimate this time dependence from a computer simulation. Another imponderable which goes into seismic detection and is all but impossible to model on a computer, is the ability of trained analysts to assess, recall and cross-check seismic data.

The second method of determining seismic capability takes these complicating features into account by simply observing a network in operation for a length of time and then assessing it from the bulletin it puts out. It is this second or operational approach which was felt to be needed at the Cambridge meeting and in this paper we shall discuss the production of a high-quality bulletin for this purpose. The significance of this data base will not be considered here, as there are many details of the bulletin which need further research before firm conclusions can be drawn.

THE NEED FOR A NEW APPROACH TO EPICENTER LIST PREPARATION

At present several agencies issue bulletins based on the detection of body waves. For instance, the seismic arrays LASA and NORSAR and Hagfors issue daily lists of seismic activity. Then the U. S. National Ocean Survey (NOS) publishes a regular summary of events based on voluntary co-operating stations throughout the world. Many individual seismologists also put out a bulletin, frequently based on what has been seen at several stations. Finally the International Seismological Center at Edinburgh publishes a bulletin which again depends on voluntary co-operating agencies and which is in some senses the most complete source of detection data for seismic events, being based on the largest number of reporting stations.

Unfortunately an assessment of detection capability based simply on reading existing bulletins would only place upper limits on the potential threshold. Whilst the bulletins reflect detections in the real earth, the information provided by contributing stations is provided on a voluntary basis. It would be unrealistic to expect these data to have been subject to the highest quality controls and a certain amount of variability inevitably results. In addition there is little uniformity in the standards of instrumentation of co-operating stations. Large arrays use computers to detect signals and furthermore are able to determine relatively accurately the direction of approach of such signals. Single stations record visually and the station operator must read the trace directly. Most importantly, stations which report rapidly cannot communicate with others in assessing whether an event has been recorded and thus may be reluctant to risk having too many false alarms in their list of detections. Three features were uppermost in our concern in planning the Seismic Month -

(i) the hybrid nature of the network and thus the variable character

of the data provided by different sources,

(ii) the need for an assessment of seismic records in the light of knowledge of what was recorded at other stations, and

(iii) the need for a more painstaking (non-voluntary) reading of records.

RAW MATERIALS

The idea of a month called the International Seismic Month (ISM) for which seismic data would be analysed in the most comprehensive way possible was discussed and approved at the Cambridge meeting, and this month was chosen as February 20 - March 19, 1972. An assessment based on winter months in the Northern Hemisphere where the majority of seismic stations are located was expected to be slightly on the pessimistic side as noise levels are a little higher in the winter than the summer.

Many agencies immediately offered collaboration and MIT Lincoln Laboratory acted as a data center for the operation. Richard Lacoss has been in command of most aspects of data handling, assessment and processing. Data in various forms and computational services have been provided by:

U. S. National Ocean Survey

Seismic Array Analysis Center, Alexandria, Virginia

Lamont-Doherty Geological Observatory

Texas Instruments Incorporated

Seismology Division, Department of Energy Mines and Resources, Ottawa, Canada

United Kingdom Atomic Energy Authority, Blacknest, England

NORSAR Data Center, Kjeller, Norway

Research Institute for National Defence, Stockholm, Sweden.

The first objective was to accumulate as reliable and extensive an epicenter list as possible based on body-wave detections. For this purpose an early data base comprised the NOS epicenter listings and the bulletins of the large arrays. Both the NOS and the array processing centers maintain extensive secondary lists of possible

events for which there is not enough corroboration from data available at the time of publication. These secondary lists were a potential large source of further events - the simple bringing together of these lists which had not previously been cross-checked was a valuable exercise in confirming events. Further data were needed however and so the following additional items were put into the data base:

(i) detections reported to NOS which could not be associated by them with any event on their epicenter list,

(ii) detections from a complete and intensive re-reading of the Canadian network,

(iii) detections from U.K.-sponsored arrays and the Hagfors array in Sweden, and

(iv) detections from an intensive rereading at MIT of a few World-Wide Network stations.

PROGRAMS FOR HANDLING THE DATA BASE

It became clear to us in late summer 1972 that although it had been possible to issue a preliminary bulletin based on a digest of bulletins available at that time with some modest additions from the growing data base, a final bulletin based on all available detections would be almost impossible to generate without much more computer assistance in bookkeeping. For example, we started with about a hundred thousand detections and even after many of these had been edited out forty thousand remained and needed assembling in the right order and associating wherever possible with events. Thus the decision was made to postpone work on the bulletin until a good interactive data analysis and display system had been built.

This system is now in operation and permits the analyst to handle data in an interactive way by means of display on a cathode ray tube. The many subprograms allow the decisions to be made by an analyst, their consequences to be rapidly worked out by the computer and the results to be returned to the analyst for immediate assessment. This mode of operation has immeasurably helped in the production of an epicenter list.

In addition to the development of a master program to present data to the analyst in as convenient a way as possible, several other major new programs have had to be written for the ISM. The most important is that for locating events. Location techniques are well-established when a set of arrival times at seismic stations is available, but procedures have had to be established for the incorporation of array information on direction of approach into the location process. A further matter that has required some attention in the new location program has been the realistic treatment of errors in data. It has been well known for some time that events are frequently located

by seismological techniques quite precisely with apparently small margins of error but the actual location, obtained from external information, is many standard deviations away from the computed location. This discrepancy arises from complexity in the deep structure of the earth and the bias is difficult to remove without quite extensive geophysical research. It is important,however, that quoted locations contain a more realistic assessment of their accuracy than heretofore. Thus the non-uniqueness of each calculation location has been evaluated and is expressed in terms of the parameters of the four-dimensional (latitude, longitude, depth, origin time) ellipsoid within which chi squared is within 1.0 of its minimum value. This information enables one to calculate the effect upon the residuals of perturbing the location (see Appendix) although we do not yet have the necessary knowledge to access with great confidence the precise level at which the errors become unacceptable. In the Seismic Month bulletin production we have assumed teleseismic P wave (20°-95°) arrival times at individual stations to have probable errors of 1.5 sec, other arrival times to have probable errors of 3.0 sec, large array slowness values to have probable errors of 0.4 sec/degree, and medium array values to have probable errors of 0.8 sec/degree. In general in adopting these values we have probably erred somewhat on the conservative side.

The nature of the location program used is discussed in more detail in an Appendix. The bulletin gives two quantities relating to the uniqueness of the location, MAXAX2 and MAXAX3, which are the maximum distances by which the epicenter and the hypocenter, respectively, may be displaced without increasing chi squared by more than 1.0. These parameters will play a major role in determining the acceptability of locations.

A value of MAXAX2 greater than a few hundred kms should certainly be regarded

as a warning that the event should not be used for further work without an attempt being made to reduce the value by the examination of more seismograms.

THE EPICENTER LIST

Table 1 is an epicenter list for the day 1972 Feb 23. Listings now exist for the whole month. All the back-up information on the quality of the location (shape and orientation of the chi-squared hyper-ellipsoid) and lists of stations used in each location are also available. In this listing however, we have tried to give a summary of the parameters that are needed for an immediate evaluation of the quality of the determination. It will be seen that not all the data associated with a given event are necessarily used. For instance arrival times have to be within 5 seconds of the predicted values to be acceptable. Conventional requirements of locating are followed. In the presence of an array velocity determination (and arrival time) at least one other arrival time is necessary. In the absence of an array four or more arrival times are needed.

The parameter MAXAX2 is a particularly valuable measure of the quality of the epicenter location. In Figure 1 we show for all events reported in the month which had a magnitude assigned to them by three or more stations the value of MAXAX2 as a function of magnitude. There are, of course, frequent problems with finding the correct m_b. Nevertheless it is clear from Figure 1 that the quality of epicenter location declines quite rapidly below m_b 4.5. Even above that number there are some events which are clearly poorly located. In some of these cases the m_b value may be seriously in error. For instance, we see event 151 on Table 1 as having an extremely high value of MAXAX2 for an m_b 4.75 event, whilst the depth determination is clearly of no use at all. However m_b has been determined from one station at $\Delta = 14^\circ$ so although we have relatively little doubt of the reality of the event its parameters are really open to the greatest doubt.

Even when we remove anomalous points like this to get Figure 1, there is still a residue of poorly located large events, and Figure 2 gives a striking demonstation of

TABLE I

EVENT	0. TIME	LAT	LONG	DEPTH	SOURCE	AVEMB	MAXMB	MINMB	MAXAX2	MAXAX3	NAT	NV	NATLOC	NVLOC	NAVEMB	NEXMB	CHI2	DEGF
132	00:01:22	15.50	- 91.22	168	S	4.47	5.03	4.08	31	120	10	1	9	1	5	0	2.2	7
133	00:13:20	- 4.89	153.47	71	S	4.46	4.69	4.11	8	8	26	1	26	1	8	0	26.3	24
134	00:39:36	14.39	118.79	293	S	3.99	4.55	3.43	44	49	5	0	5	0	2	0	1.5	1
135	03:07:04	43.88	148.30	42	S	4.95	5.52	4.13	14	14	61	4	26	4	27	5	9.2	30
136	03:21:28	43.94	148.17	29	S	4.79	5.25	3.80	16	16	43	3	26	3	19	3	13.5	28
137	03:42:42	44.14	148.28	37	S	4.87	5.40	3.98	20	20	54	3	26	3	27	2	9.4	28
138	04:38:49	-16.91	-175.18	264	S	4.31	5.06	3.54	20	20	26	2	25	2	6	3	35.7	25
139	05:11:07	45.67	149.21	0	SR	3.85	4.10	3.58	1920	4757	3	2	3	2	5	0	1.6	3
140	07:30:50	18.31	- 68.87	74	S	4.85	5.25	3.66	25	25	42	3	25	3	22	3	8.2	27
141	07:41:21	- 3.80	154.11	433	S	4.75	5.18	3.85	15	15	55	3	20	2	14	1	9.3	20
142	08:20:25	21.14	120.20	0	SR	4.12	4.45	3.80	75	162	5	0	5	0	2	0	3.7	1
143	09:39:35	2.14	126.54	90	S	4.95	5.38	4.12	10	42	50	2	27	2	12	3	11.4	27
144	10:11:04	34.71	25.53	107	S	3.89	4.47	3.48	41	43	9	3	8	2	9	0	1.7	8
145	11:36:01	51.86	171.96	61	S	4.62	5.19	3.96	15	15	40	3	25	3	26	3	10.7	27
146	11:53:04	-14.87	167.14	137	S	0.00	0.00	0.00	31	31	8	0	8	0	0	0	15.0	4
147	12:55:31	36.90	71.65	155	S	3.92	4.15	3.74	59	89	8	1	6	1	4	0	2.8	4
148	14:00:42	37.83	72.06	0	SR	4.28	5.25	4.01	54	158	8	3	7	3	6	1	3.6	10
149	14:27:14	1.52	- 91.58	369	S	3.83	4.26	3.47	505	872	8	2	8	2	7	0	0.9	8
150	14:39:34	- 4.93	151.21	198	S	0.00	0.00	0.00	34	34	6	0	5	0	0	0	0.0	0
151	15:38:07	-14.55	30.60	0	SR	4.75	4.75	4.75	530	13003	6	0	4	0	1	0	0.4	1
152	15:49:06	40.14	-117.48	0	SR	0.00	0.00	0.00	27	13190	5	0	5	0	0	0	0.2	1
153	16:48:22	- 6.82	129.40	163	S	4.34	4.34	4.34	21	63	13	0	9	0	1	0	1.5	5
154	16:55:2[illegible]	54.24	-167.82	366	S	3.14	3.14	3.14	222	398	2	1	2	1	2	0	0.0	0
155	18:09:2[illegible]	16.26	- 91.68	53	S	4.03	4.73	3.79	84	84	7	3	6	2	8	1	32.4	6
156	18:19:06	-15.44	-172.57	81	S	5.62	6.32	4.79	28	28	98	3	21	3	18	2	31.8	23
157	18:40:57	- 3.35	- 80.06	29	S	3.95	4.49	3.52	129	129	8	2	6	2	6	0	0.5	6
158	19:05:06	- 8.16	147.73	0	SR	0.00	0.00	0.00	20	85	7	0	7	0	0	0	1.7	3
159	19:16:07	-13.44	-173.50	0	SR	4.20	4.67	3.74	207	368	6	1	6	1	5	0	1.1	4
160	20:18:04	- 5.21	-145.09	0	SR	0.00	0.00	0.00	27	89	8	0	8	0	0	0	3.0	4
161	20:53:07	-21.06	- 68.34	137	S	3.71	3.71	3.71	867	957	3	1	2	1	2	0	0.0	0
162	22:25:33	33.28	132.41	0	SR	0.00	0.00	0.00	59	13498	5	0	5	0	0	0	5.3	2
163	23:13:42	35.60	53.17	0	SR	4.68	4.68	4.68	109	111	5	0	5	0	1	0	0.4	2

Nomenclature for Sample Event List for 23 February 1973 (Table 1).

Columns are:

EVENT	=	Sequential count
O. TIME	=	Origin Time
LAT	=	Latitude
LONG	=	Longitude
DEPTH	=	Depth in km
SOURCE	=	Indicates source of hypocenter. If it is 'S' it was run free and 'SR' means depth restrained.
AVEMB	=	m_b assigned to the event. Value is an average of values obtained from P arrivals in the 10^o to 105^o range.
MAXMB	=	Largest reported m_b.
MINMB	=	Smallest reported m_b.
MAXAX2	=	Length in km of largest epicenter error ellipse semiaxis.
MAXAX3	=	Length in km of largest hypocenter error ellipsoid semiaxis.
NAT	=	Number of items associated with the event and which are arrival times.
NV	=	Number of associated items which are velocities.
NATLOC	=	Number of arrival times used in getting location.
NVLOC	=	Number of velocities used in getting location. (NATLOC and NVLOC will not exceed 30 due to computer program limitations.)
NAVEMB	=	Number of m_b values averaged to get AVEMB.
NEXMB	=	Number of m_b values not used in calculating AVEMB because values were more than 0.6 units away from AVEMB.
CHI2	=	Chi square goodness of fit parameter.
DEGF	=	Degrees of freedom for CHI2.

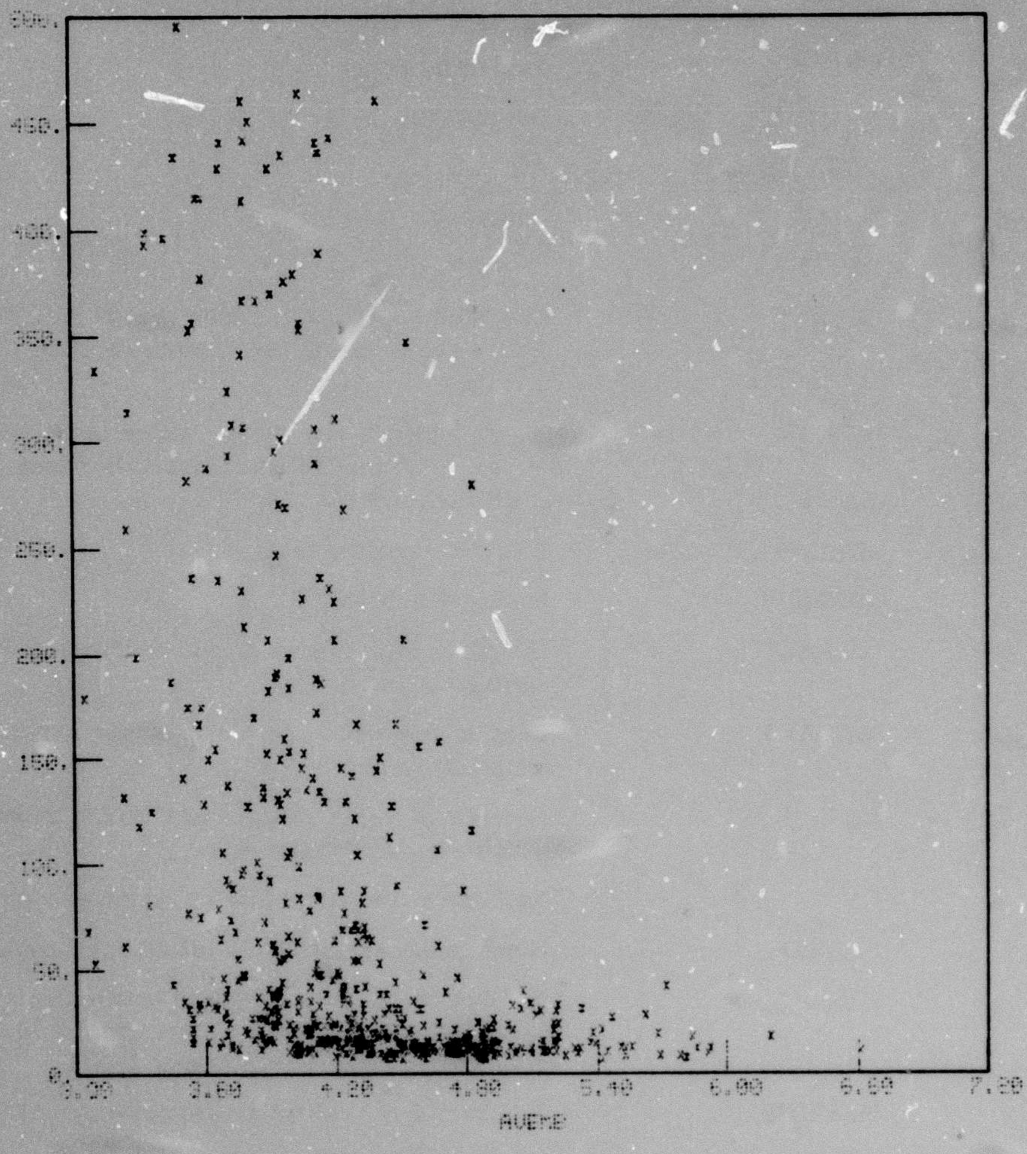

Fig. 1. Maximum epicenter error ellipse semiaxis (MAXAX2) in km vs m_b (AVEMB). All seismic month events with three or more stations contributing to m_b are included (625 events).

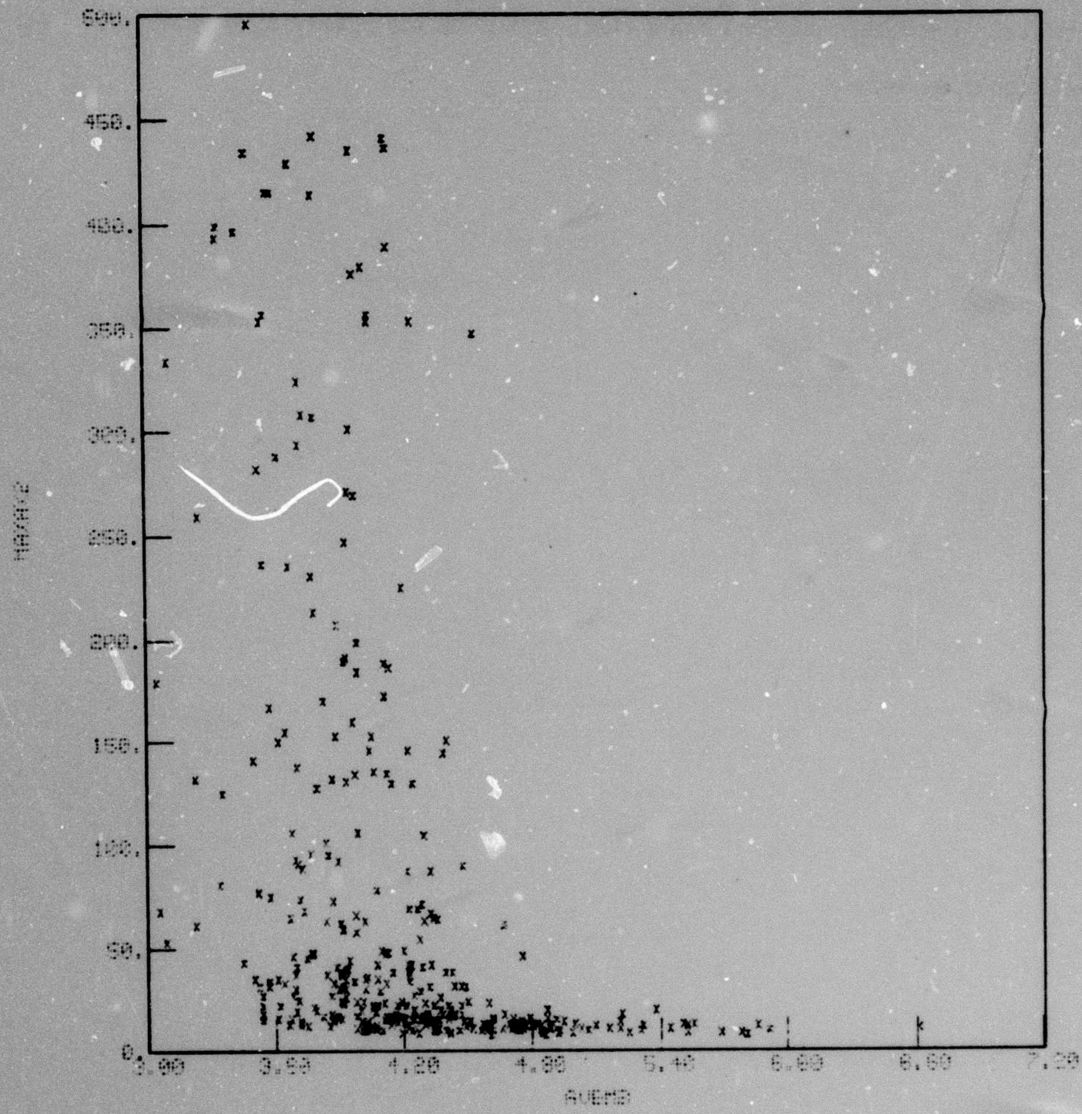

Fig. 2. Maximum epicenter error ellipse semiaxis (MAXAX2) in km vs m_b (AVEMB). All seismic month events with three or more stations contributing to m_b and located more than 20^{o} North (381 events).

the cause of this. In Figure 2 only events located north of 20°N are plotted. It is clear that the lack of southern stations has a clear impact on the quality of the epicenter list, even at high magnitudes.

DEPTH ESTIMATION

The 'depth' column in Table 1 contains a value that may come from one of three sources:

(i) A determination by P-wave travel times alone

(ii) A joint determination by P-waves and reflected phases

(iii) A restrained depth (indicated by an SR in the next column)

An event will be restrained to 0 or 700 km depth if the location process would place it at negative depth or at greater than 700 km. The process of restraining the depth often leads, as will be clear from Table 1, to enormous and meaningless values for MAXAX3. On the other hand a determination in which depth phases have been used will generally lead to a situation in which depth is better determined than epicenter so MAXAX3 is in fact the same at MAXAX2.

THE ISM EPICENTER LIST COMPARED WITH OTHER SOURCES

In Table 2 we show an abstract of Table 1 together with the NOS list, and the LASA and NORSAR bulletins for the same day. This is a relatively small sample and more complete NOS statistics will be presented later in this paper. Nonetheless it gives an impression of the composition of the ISM list. Six of the 32 events had featured on no previous bulletin although they may have been on one or more of the secondary lists mentioned previously. On this day (but not in general) NORSAR reported no events that ISM could not verify (i.e., with at least one additional station) but LASA produced five, shown in Table 3. One of these is almost certainly pP from event 141; for the remaining four we can present no further evidence at present.

The total number of events on the epicenter list is 946. In Figure 3 we show an interval histogram of events to which magnitudes have been assigned. It is apparent on comparison with the NOS bulletin that ISM has contributed little new above m_b 5.0. However, below 5.0 the ISM contributes an increasing number of new events. The ISM reports 474 events with $m_b \geq 4.0$ whereas NOS reports 287. ISM also reports 164 events for which no magnitude is yet available and 308 with $m_b < 4.0$. The corresponding NOS figures are 38 and 28. We wish to emphasize that this comparison is not meant to reflect unfavorably on the NOS bulletin which is produced under completely different conditions and with different requirements.

TABLE 2

NOS, LASA, and NORSAR bulletin information for Seismic Month events of 23 February 1972.

Seismic Month List					NOS				LASA			NORSAR		
Event	Lat	Long	Depth	M_B	Lat	Long	Depth	M_B	Lat	Long	M_B	Lat	Long	M_B
132	15.5	-91.2	168	4.5					17.	-92.	4.2			
133	-4.9	153.5	71	4.5	-5.0	153.5	74	4.6						
134	14.4	118.8	293	4.0										
135	43.9	148.3	42	4.9	43.7	148.4	41D	4.8	44.	149.	4.8	44.	149.	4.9
136	43.9	148.2	29	4.8	44.2	148.4	40G	4.7	44.	149.	4.6	44.	148.	4.8
137	44.1	148.3	37	4.9	43.9	148.3	39D	4.9	44.	149.	4.6	44.	148.	5.0
138	-16.9	-175.2	264	4.3					-15.	-174.	4.4			
139	45.7	149.2	0	3.9					45.	150.	3.7			
140	18.3	-68.9	74	4.9	18.2	-68.8	73	4.5	16.	-69.	4.9	18.	-69.	4.5
141	-3.8	154.1	433	4.8	-3.8	154.1	438	4.8	-4.	155.	5.5	-6.	151.	4.6
142	21.1	120.2	0	4.1								15.	120.	4.2
143	2.1	126.6	90	5.0	2.0	126.6	86	4.9						
144	34.7	25.5	107	3.9					32.	27.	4.4	41.	24.	3.3
145	51.9	172.0	61	4.6	51.6	172.2	N	4.7	52.	172.	4.7	51.	171.	3.9
146	-14.9	167.1	137	—	-14.7	167.4	106	—				21.	170.	4.7
147	36.9	71.7	155	3.9	36.8	71.5	177	3.8				38.	70.	4.1
148	37.8	72.1	0	4.3								35.	73.	4.3
149	1.5	-91.6	369	3.8					0.	-92.	4.3			
150	-4.9	151.2	198	—	-4.9	151.3	216	5.0						
151	-14.6	30.6	0	4.8										
152	40.1	-117.5	0	—	40.2	-117.5	10G	—						
153	-6.8	129.4	163	4.3										
154	54.2	-167.8	366	3.1					53.	-172.	3.7			
155	16.3	-91.7	53	4.0					18.	-96.	4.2	22.	-94.	4.2
156	-15.4	-172.6	81	5.6	-15.1	-173.0	51	5.7	-18.	-175.	5.7	-19.	-173.	5.0
157	-3.4	-80.1	29	4.0					-3.	-81.	4.1			
158	-8.2	147.7	0	—	-8.1	147.7	N	—						
159	-13.4	-173.5	0	4.2					-16.	-173.	4.6			
160	-5.2	145.1	0	—										
161	-21.1	-68.3	137	3.7					-21.	-69.	3.9			
162	33.3	132.4	0	—										
163	35.6	53.2	0	4.7										

Note: Columns 1-4 are taken from Table 1 and the remaining columns show entries from other sources. A blank line indicates the event was not in the corresponding bulletin.

TABLE 3

LASA Bulletin Assigned Values

Arrival Time	Latitude	Longitude	Magnitude	Comments
0:26:48	-9	-174	4.0	Cannot verify
7:55:54	-3	157	4.9	pP to event at 7:41:21
9:55:03	86	139	3.7	Cannot verify
16:53:02	-26	-177	4.4	Cannot verify
19:49:29	55	163	3.7	Cannot verify

Note: LASA bulletin entries of 23 February 1972 which have not yet been verified or which correspond to phases of an event in Table 1.

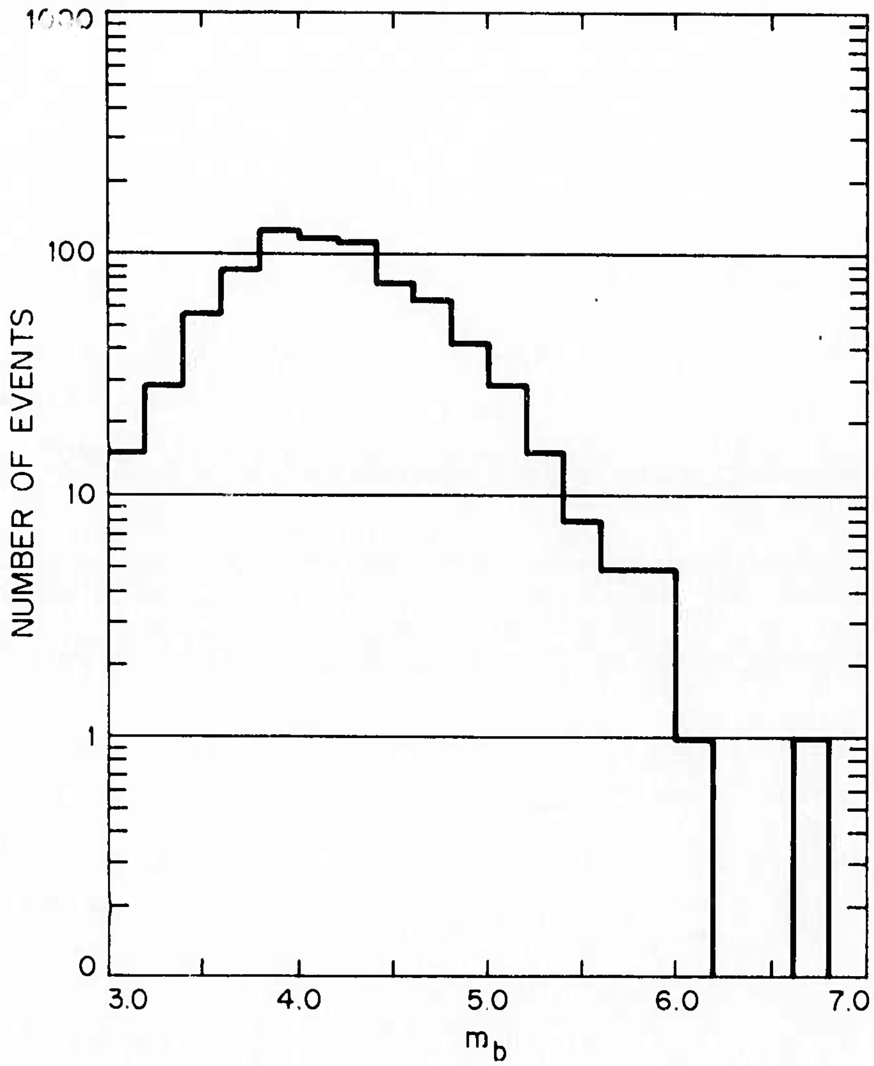

Fig. 3. Incremental histogram of Seismic Month body wave magnitudes. Increment used is 0.2 magnitude units.

HOW OPTIMAL IS THE ISM?

We are aware of at least two ways in which our present epicenter list could be improved.

The first way is best described by means of an example. An event of m_b 4.5 has a MAXAX2 value of 347 kms (this point is prominent in Figure 2). Since this value is anomalously large for the magnitude we looked at the list of detections associated with the event. These stations were in North America and Scandinavia (see Figure 4) and it is clear that coverage is poor, even with the contributions of arrays. However we have rejected a detection at Matsushiro (MAT) because it gave a residual of 14.3 sec. This would be reasonable if the event were well located, but the large value of MAXAX2 clearly indicates we should reconsider the Matsushiro detection. When we put it back into the location process we find that the epicenter moves about 200 km, the Matsushiro residual can be reduced to 3.1 second and MAXAX2 to 116 km. There will clearly be many instances in the bulletin where a re-examination of this form could reduce MAXAX2.

The second way we might have improved the bulletin would be to have an analyst read every station of the World-Wide Network to supplement the computer readings of digital stations and the voluntary (and therefore patchy) readings of World-Wide Network and other stations. Up to the present we have had to make do without this, although an analyst has read two stations in their entirety. How much would have been gained by the investment of much more analyst's time? A relatively simple, if somewhat unsophisticated answer to this can be found by the following procedure:

(i) Find an event with a large value of MAXAX2, coming (say) from one array and one single station,

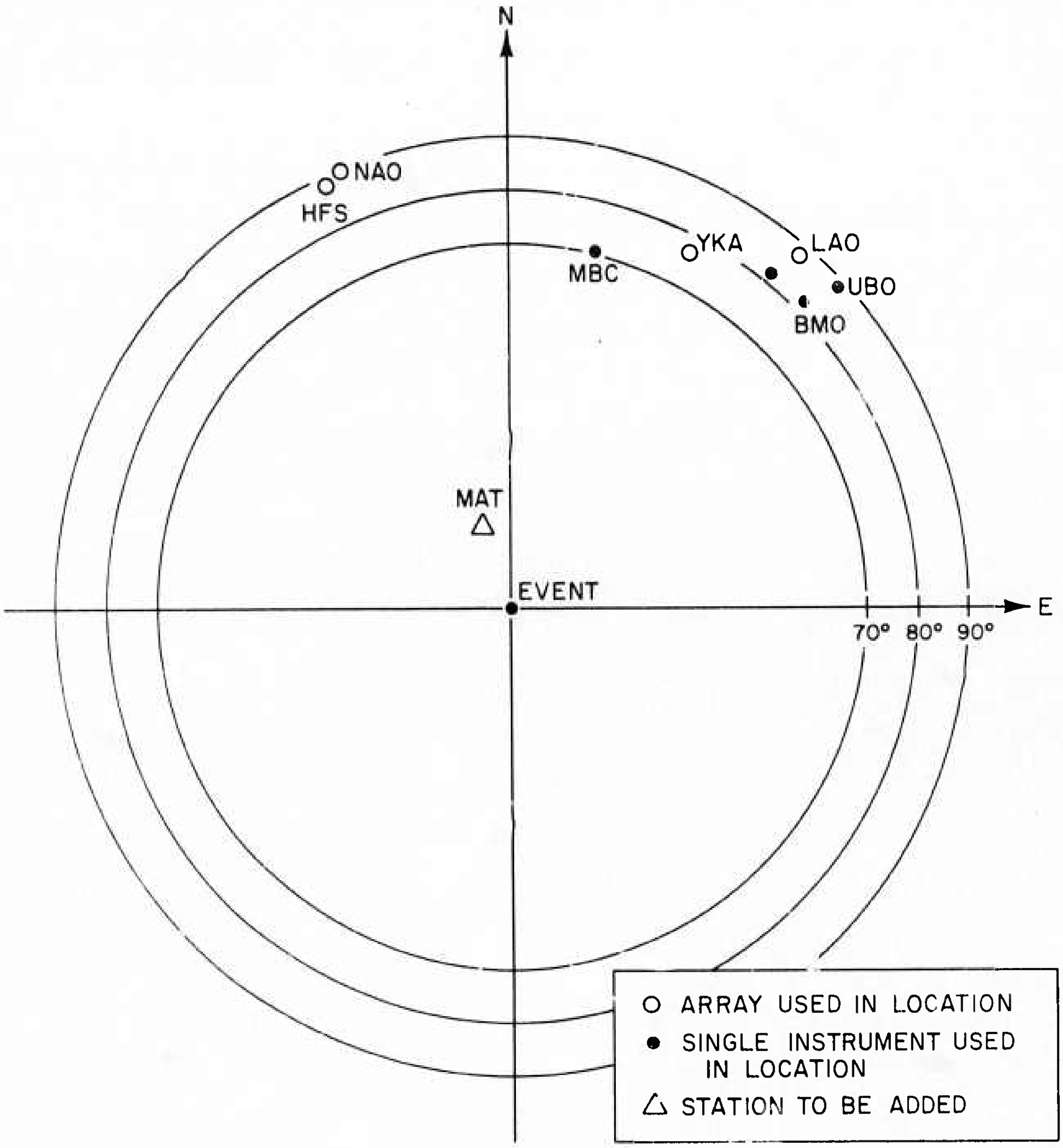

Fig. 4. Relative location of reporting stations and an event with large potential location error. The addition of station MAT reduced the location error variable (MAXAX2) from 347 to 119 kilometers.

(ii) Select other nearby stations and search their records at the expected arrival times,

(ii) Re-locate with an expanded data-base.

By this means we had hoped to bring hindsight, unavailable to the station operator, to bear on deciding what were acceptable detections.

Results have been disappointing, based on a very small sample so far. We have yet to find a good extra station detection which would lead to shrinkage of MAXAX2. The reason for this appears to be that, in general, poorly located events are relatively remote and finding additional stations (particularly those who mail their seismograms regularly) is frequently impossible. It is thus unlikely that the operation as we have been running it is far from optimal. Certainly it isn't clear at present that the additional expense of extensive further readings of seismograms is warranted.

LONG PERIOD RESULTS

Data on long period detections have been supplied by:

(i) A complete reading of the Canadian Network and selected World-Wide Network seismograms

(ii) The Hagfors, Gauribidanur and Yellowknife arrays

(iii) A complete reading of the Lamont-sponsored long period experiment seismograms.

(iv) LASA, NORSAR and ALPA.

At the present data from all except LASA, NORSAR and ALPA have been integrated into the data base and are available for study, although as yet little has been done with the long period data as the full epicenter list was needed first. However a quick scan has been made of the data at hand for 1972 February 23, and the following remarks can be made. Of the 32 events that occurred during 23 February, 14 had surface waves that could be identified with some confidence. Six additional surface waves were identified but large arrival time or amplitude anomalies made any correlation of these detections with specific events dubious. The remaining 12 events had no identifiable surface waves at any of the stations, networks or arrays studied. Of the 18 events with no clear surface waves 4 were deeper than 100 km, with little doubt cast on the depth from the error estimates (events 135, 139, 147 and 151), and the remainder had rather poor detph estimates. So 14 events had detectable surface waves, 4 events were deep, and the remaining 14 events were of uncertain depths and revealed no surface waves.

FURTHER WORK

There is clearly much work still to be done on improving the quality of the epicenter list. Reductions in MAXAX2 for selected events, and an increase in the number of stations contributing to m_b determinations are our first aims. We fully expect to be able to make more remarks on network capability as a function of region, and we are also interested in determining how well we could have done with a subset of (say) 25 selected stations. We cannot yet predict what the long period study will reveal.

ACKNOWLEDGEMENTS

All members of the Lincoln Laboratory Seismic Discrimination Group have contributed significantly to the Lincoln ISM effort. All, to some extent, should be considered authors of this report. The listed authors have been limited to the Group Leader and Associate Leader only to avoid listing all Group members as authors. Special mention must be made of Mr. Russell Needham for accomplishing most of the data processing, to Ms. Leslie Turek for programming data management systems, and to Dr. Bruce Julian for event location programs.

APPENDIX (by B. R. Julian)

The technique used to calculate hypocenter locations and their uncertainties for the ISM differs significantly in two ways from conventional methods. Firstly, $dT/d\Delta$ and azimuth data from seismic arrays, as well as arrival time data, may be used. The inclusion of such data will have a significant effect only for the smallest events, for which arrival time data are very sparse (less than 4 or 5 data, say). In such cases, array data will enable a crude location to be obtained, when otherwise the problem would be completely indeterminate. The method for incorporating such array data is a straightforward extension of standard least-squares fitting techniques.

The second difference between our method and standard practice lies in the method used to estimate the range of possible uncertainty in the locations. With conventional techniques the magnitude of the errors of observation is estimated from the quality of the fit to the data, the errors being assumed to be random and uncorrelated. In fact, however, these "errors" are produced primarily by lateral velocity variations in the earth and are thus systematically related to each other and can introduce systematic errors in the calculated locations. In other words, velocity variations in the earth produce travel time anomalies which often can be "cancelled out" by a suitable mislocation of the hypocenter, and the resulting internal consistency of the fit to the data may be deceptively good. The clearest indication of such behavior comes from explosions with known hypocentral parameters, for which it very often happens that the true location lies far outside the estimated uncertainty bounds. Flinn (1965), for example, calculated locations for eleven Nevada explosions and found that for four of them the true depth was inconsistent with the calculated uncertainty bounds. The calculated depths and their standard deviations for these four events were 39.0±9.7 km (AARDVARK), 51.8±3.6 km

(MISSISSIPPI), 48.3±2.8 km (BILBY), and 36.4±4.6 km (SHOAL). Clearly such bounds may be severely misleading.

Therefore we have chosen to estimate the problem errors in the data a priori, on the basis of experience with events of known location, etc. These estimates will of course be considerably larger than the actual measurement errors, and will generally be larger than the standard deviations of the data relative to a best-fit hypocenter, but they will more realistically represent the true uncertainty in the location. We can then calculate the range of hypocentral parameters which will fit the data within the estimated errors. More precisely, the goodness of fit is evaluated in terms of the quantity chi squared, defined as

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{\epsilon_i}{\sigma_i}\right)^2$$

where ϵ_i is the residual between the ith datum and the value calculated from tables and an assumed location, σ_i is the a priori error estimate, and N is the number of data. The calculated confidence ellipsoid then specifies the region of space within which $\chi_0^2 \leq \chi^2 \leq \chi_0^2 + 1$, where χ_0^2 is the minimum value of χ^2, corresponding to the best fit location. The ellipsoid axes are thus not to be regarded as definitive limits, but rather as tools which enable one to calculate the goodness of fit to the data corresponding to any desired hypocenter perturbation.

It should be emphasized that we are taking care not to interpret χ^2 too literally in terms of probabilities. Standard tables of the Chi-squared distribution are based upon the assumption of independent, normally distributed errors, which as mentioned above, does not apply here. For the present we use χ^2 merely as a rough estimate of whether the errors are about the size we expected them to be. The error estimates used here are guesses, and more research, using independently located events, is needed to in-

crease out knowledge of the size of travel time variations in the real earth so that we may refine our interpretation of the confidence regions.